

**Time-Dependent  $CP$  Asymmetries in  $B^0 \rightarrow K_S^0 \pi^0 \gamma$  transition**

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## Abstract

We present measurements of  $CP$ -violation parameters in  $b \rightarrow s\gamma$  transitions based on a sample of  $386 \times 10^6$   $B\bar{B}$  pairs collected at the  $\Upsilon(4S)$  resonance with the Belle detector at the KEKB energy-asymmetric  $e^+e^-$  collider. One neutral  $B$  meson is fully reconstructed in the  $B^0 \rightarrow K_S^0\pi^0\gamma$  decay channel irrespective to the  $K_S^0\pi^0$  intermediate state. The flavor of the accompanying  $B$  meson is identified from its decay products.  $CP$ -violation parameters are obtained from the asymmetries in the distributions of the proper-time intervals between the two  $B$  decays.

We obtain the following results for the  $K_S^0\pi^0$  invariant mass covering the full range up to  $1.8\text{ GeV}/c^2$ :

$$\begin{aligned}\mathcal{S}_{K_S^0\pi^0\gamma} &= +0.08 \pm 0.41(\text{stat}) \pm 0.10(\text{syst}), \\ \mathcal{A}_{K_S^0\pi^0\gamma} &= +0.12 \pm 0.27(\text{stat}) \pm 0.10(\text{syst}).\end{aligned}$$

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## INTRODUCTION

In the Standard Model (SM),  $CP$  violation arises from an irreducible phase, the Kobayashi-Maskawa (KM) phase [1], in the weak-interaction quark-mixing matrix. The phenomena of time-dependent  $CP$  violation in decays through radiative penguin processes such as  $b \rightarrow s\gamma$  are sensitive to physics beyond the SM. Within the SM, the photon emitted from a  $B^0$  ( $\bar{B}^0$ ) meson is dominantly right-handed (left-handed). Therefore the polarization of the photon carries information on the original  $b$ -flavor and the decay is, thus, almost flavor-specific. As a result, the SM predicts a small asymmetry [2, 3] and any significant deviation from this expectation would be a manifestation of new physics. It was pointed out that in decays of the type  $B^0 \rightarrow P^0 Q^0 \gamma$ , where  $P^0$  and  $Q^0$  represent any  $CP$  eigenstate spin-0 neutral particles (e.g.  $P^0 = K_S^0$  and  $Q^0 = \pi^0$ ), many new physics effects on the mixing-induced  $CP$  violation do not depend on the resonant structure of the  $P^0 Q^0$  system [4].

At the KEKB energy-asymmetric  $e^+e^-$  (3.5 on 8.0 GeV) collider [5], the  $\Upsilon(4S)$  is produced with a Lorentz boost of  $\beta\gamma = 0.425$  along the  $z$  axis, which is defined as the direction antiparallel to the  $e^+$  beam direction. In the decay chain  $\Upsilon(4S) \rightarrow B^0 \bar{B}^0 \rightarrow f_{\text{sig}} f_{\text{tag}}$ , where one of the  $B$  mesons decays at time  $t_{\text{sig}}$  to a final state  $f_{\text{sig}}$ , which is our signal mode, and the other decays at time  $t_{\text{tag}}$  to a final state  $f_{\text{tag}}$  that distinguishes between  $B^0$  and  $\bar{B}^0$ , the decay rate has a time dependence given by

$$\mathcal{P}(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \left\{ 1 + q \left[ \mathcal{S} \sin(\Delta m_d \Delta t) + \mathcal{A} \cos(\Delta m_d \Delta t) \right] \right\}. \quad (1)$$

Here  $\mathcal{S}$  and  $\mathcal{A}$  are  $CP$ -violation parameters,  $\tau_{B^0}$  is the  $B^0$  lifetime,  $\Delta m_d$  is the mass difference between the two  $B^0$  mass eigenstates,  $\Delta t$  is the time difference  $t_{\text{sig}} - t_{\text{tag}}$ , and the  $b$ -flavor charge  $q = +1$  ( $-1$ ) when the tagging  $B$  meson is a  $B^0$  ( $\bar{B}^0$ ). Since the  $B^0$  and  $\bar{B}^0$  mesons are approximately at rest in the  $\Upsilon(4S)$  center-of-mass system (c.m.s.),  $\Delta t$  can be determined from the displacement in  $z$  between the  $f_{\text{sig}}$  and  $f_{\text{tag}}$  decay vertices:  $\Delta t \simeq (z_{\text{sig}} - z_{\text{tag}})/(\beta\gamma c) \equiv \Delta z/(\beta\gamma c)$ .

For  $B^0 \rightarrow K_S^0 \pi^0 \gamma$ , the  $K_S^0$  vertex is displaced from the  $B$  vertex and often lies outside of the silicon vertex detector (SVD). When the  $K_S^0$  vertex can be reconstructed inside the SVD, the time-dependent  $CP$  asymmetry can be measured. Measurements of such  $CP$  asymmetries were previously reported by BABAR [6] and Belle [7] in the  $B^0 \rightarrow K^{*0}(\rightarrow K_S^0 \pi^0) \gamma$  decay:

$$\begin{aligned} \mathcal{S}_{K^{*0}\gamma} &= 0.25 \pm 0.63 \pm 0.14 & (\text{BABAR}) \\ \mathcal{S}_{K^{*0}\gamma} &= -0.79_{-0.50}^{+0.63} \pm 0.10 & (\text{Belle}). \end{aligned}$$

Belle also measured these asymmetries with an extended  $M_{K_S^0 \pi^0}$  mass region [7] ( $M_{K_S^0 \pi^0} < 1.8 \text{ GeV}/c^2$ ):

$$\mathcal{S}_{K_S^0 \pi^0 \gamma} = -0.58_{-0.38}^{+0.46} \pm 0.11 \quad (\text{Belle}).$$

In this analysis, we update the  $CP$  measurements for  $B^0 \rightarrow K_S^0 \pi^0 \gamma$  in the mass region  $M_{K_S^0 \pi^0} < 1.8 \text{ GeV}/c^2$  with an additional dataset of  $111 \times 10^6$   $B\bar{B}$  pairs.

The Belle detector is a large-solid-angle magnetic spectrometer that consists of an SVD, a 50-layer central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an

electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect  $K_L^0$  mesons and to identify muons (KLM). The detector is described in detail elsewhere [8]. Two inner detector configurations were used. A 2.0 cm beampipe and a 3-layer silicon vertex detector (SVD1) was used for the first sample of  $152 \times 10^6$   $B\bar{B}$  pairs, while a 1.5 cm beampipe, a 4-layer silicon detector (SVD2) and a small-cell inner drift chamber were used to record the remaining  $234 \times 10^6$   $B\bar{B}$  pairs [9].

## EVENT SELECTION, FLAVOR TAGGING AND VERTEX RECONSTRUCTION

### Event Selection for $K_S^0\pi^0\gamma$

For high energy prompt photons, we select an isolated cluster in the ECL that has no corresponding charged track, and has the largest energy in the c.m.s. We require the shower shape to be consistent with that of a photon. In order to reduce the background from  $\pi^0$  and  $\eta$  mesons, we exclude photons compatible with  $\pi^0 \rightarrow \gamma\gamma$  or  $\eta \rightarrow \gamma\gamma$  decays; we reject photon pairs that satisfy  $\mathcal{L}_{\pi^0} \geq 0.18$  or  $\mathcal{L}_{\eta} \geq 0.18$ , where  $\mathcal{L}_{\pi^0(\eta)}$  is a  $\pi^0$  ( $\eta$ ) likelihood described in detail elsewhere [10]. The polar angle of the photon direction in the laboratory frame is restricted to the barrel region of the ECL ( $33^\circ < \theta_\gamma < 128^\circ$ ), but is extended to the end-cap regions ( $17^\circ < \theta_\gamma < 150^\circ$ ) for the second data sample due to the reduced material in front of the ECL.

Neutral kaons ( $K_S^0$ ) are reconstructed from two oppositely charged pions that have an invariant mass within  $\pm 6 \text{ MeV}/c^2$  ( $2\sigma$ ) of the  $K_S^0$  nominal mass. The  $\pi^+\pi^-$  vertex is required to be displaced from the interaction point (IP) in the direction of the pion pair momentum [11]. Neutral pions ( $\pi^0$ ) are formed from two photons with the invariant mass within  $\pm 16 \text{ MeV}/c^2$  ( $3\sigma$ ) of the  $\pi^0$  mass. The photon momenta are then recalculated with a  $\pi^0$  mass constraint and we require the momentum of  $\pi^0$  candidates in the c.m.s. to be greater than  $0.3 \text{ GeV}/c$ . The  $K_S^0\pi^0$  invariant mass,  $M_{K_S^0\pi^0}$ , is required to be less than  $1.8 \text{ GeV}/c^2$ .

$B^0$  mesons are reconstructed by combining  $K_S^0$ ,  $\pi^0$  and  $\gamma$  candidates. We form two kinematic variables: the energy difference  $\Delta E \equiv E_B^{\text{c.m.s.}} - E_{\text{beam}}^{\text{c.m.s.}}$  and the beam-energy constrained mass  $M_{\text{bc}} \equiv \sqrt{(E_{\text{beam}}^{\text{c.m.s.}})^2 - (p_B^{\text{c.m.s.}})^2}$ , where  $E_{\text{beam}}^{\text{c.m.s.}}$  is the beam energy,  $E_B^{\text{c.m.s.}}$  and  $p_B^{\text{c.m.s.}}$  are the energy and the momentum of the candidate in the c.m.s. Candidates are accepted if they have  $M_{\text{bc}} > 5.2 \text{ GeV}/c^2$  and  $-0.5 \text{ GeV} < \Delta E < 0.5 \text{ GeV}$ .

We reconstruct  $B^+ \rightarrow K_S^0\pi^+\gamma$  candidates in a similar way as the  $B^0 \rightarrow K_S^0\pi^0\gamma$  decay in order to reduce the cross-feed background from  $B^+ \rightarrow K_S^0\pi^+\gamma$  in  $B^0 \rightarrow K_S^0\pi^0\gamma$ . The  $B^+ \rightarrow K_S^0\pi^+\gamma$  events are also used for various crosschecks. For a  $\pi^+$  candidate, we require that the track originates from the IP and that the transverse momentum is greater than  $0.1 \text{ GeV}/c$ . We also require that the  $\pi^+$  candidate cannot be identified as any other particle species ( $K^+$ ,  $p^+$ ,  $e^+$ , and  $\mu^+$ ).

Candidate  $B^+ \rightarrow K_S^0\pi^+\gamma$  and  $B^0 \rightarrow K_S^0\pi^0\gamma$  decays are selected simultaneously; we allow only one candidate for each event. The best candidate selection is based on the event likelihood ratio  $\mathcal{R}_{\text{s/b}}$  that is obtained from a Fisher discriminant  $\mathcal{F}$  [12], which uses the extended modified Fox-Wolfram moments [13] as discriminating variables. We select the candidate that has the largest  $\mathcal{R}_{\text{s/b}}$ . The signal region is defined as  $-0.2 \text{ GeV} < \Delta E < 0.1 \text{ GeV}$  and  $5.27 \text{ GeV}/c^2 < M_{\text{bc}} < 5.29 \text{ GeV}/c^2$ .

We use events outside the signal region as well as large Monte Carlo (MC) samples

to study the background components. The dominant background is from continuum light quark pair production ( $e^+e^- \rightarrow q\bar{q}$  with  $q = u, d, s, c$ ), which we refer to as  $q\bar{q}$  hereafter. In order to reduce the  $q\bar{q}$  background contribution, we form another event likelihood ratio  $\mathcal{R}_{s/b}^{\text{BH}}$  by combining  $\mathcal{R}_{s/b}$  with  $\cos\theta_H$  and  $\cos\theta_B$ , where  $\theta_B$  is the polar angle of the  $B$  meson candidate momentum in the laboratory frame, and  $\theta_H$  is the angle between the  $B$  candidate momentum and the daughter  $K_S^0$  momentum in the rest frame of the  $K_S^0\pi$  system. Since the relative background contribution will be smaller in the region of the  $K^*$ , we introduce two  $K_S^0\pi^0$  invariant mass regions: MR1, defined as  $0.8\text{ GeV}/c^2 < M_{K_S^0\pi^0} < 1.0\text{ GeV}/c^2$ , and MR2 which is defined as  $M_{K_S^0\pi^0} < 1.8\text{ GeV}/c^2$  after excluding MR1. The specific  $\mathcal{R}_{s/b}^{\text{BH}}$  selection criteria applied depend on both the mass region and flavor tagging information. After applying all other selection criteria described so far, 77% of the  $q\bar{q}$  background is rejected while 87% of the  $K^{*0}\gamma$  signal is retained in MR1; in MR2, 87% of the  $q\bar{q}$  is rejected while 68% of the  $K^{*0}\gamma$  signal is retained. Background contributions from  $B$  decays, which are considerably smaller than  $q\bar{q}$ , are dominated by cross-feed from other radiative  $B$  decays including  $B^+ \rightarrow K_S^0\pi^+\gamma$ .

### Flavor Tagging

The  $b$ -flavor of the accompanying  $B$  meson is identified from inclusive properties of particles that are not associated with the reconstructed signal decay. The algorithm for flavor tagging is described in detail elsewhere [14]. We use two parameters,  $q$  defined in Eq. (1) and  $r$ , to represent the tagging information. The parameter  $r$  is an event-by-event flavor-tagging dilution factor that ranges from 0 to 1;  $r = 0$  when there is no flavor discrimination and  $r = 1$  implies unambiguous flavor assignment. It is determined by using MC data and is only used to sort data into six  $r$  intervals. The wrong tag fraction  $w$  and the difference  $\Delta w$  in  $w$  between the  $B^0$  and  $\bar{B}^0$  decays are determined for each of the six  $r$  intervals from data [11].

### Vertex Reconstruction

The vertex position of the signal-side decay is reconstructed from the  $K_S^0$  trajectory with a constraint on the IP; the IP profile ( $\sigma_x \simeq 100\text{ }\mu\text{m}$ ,  $\sigma_y \simeq 5\text{ }\mu\text{m}$ ,  $\sigma_z \simeq 3\text{ mm}$ ) is convolved with the finite  $B$  flight length in the plane perpendicular to the  $z$  axis. Both pions from the  $K_S^0$  decay are required to have enough hits in the SVD in order to reconstruct the  $K_S^0$  trajectory with high resolution: at least one layer with hits on both sides and at least one additional hit in the  $z$  side of the other layers for SVD1, and at least two layers with hits on both sides for SVD2. The reconstruction efficiency depends not only on the  $K_S^0$  momentum but also on the SVD geometry. The efficiency with SVD2 (51%) is significantly higher than with SVD1 (40%) because of the larger detection volume. The other (tag-side)  $B$  vertex determination is the same as that for the  $B^0 \rightarrow \phi K_S^0$  analysis [11].

### SIGNAL YIELD EXTRACTION

Figure 1 shows the  $M_{\text{bc}}$  ( $\Delta E$ ) distribution for the reconstructed  $K_S^0\pi^0\gamma$  candidates within the  $\Delta E$  ( $M_{\text{bc}}$ ) signal region after flavor tagging and vertex reconstruction. The signal yield

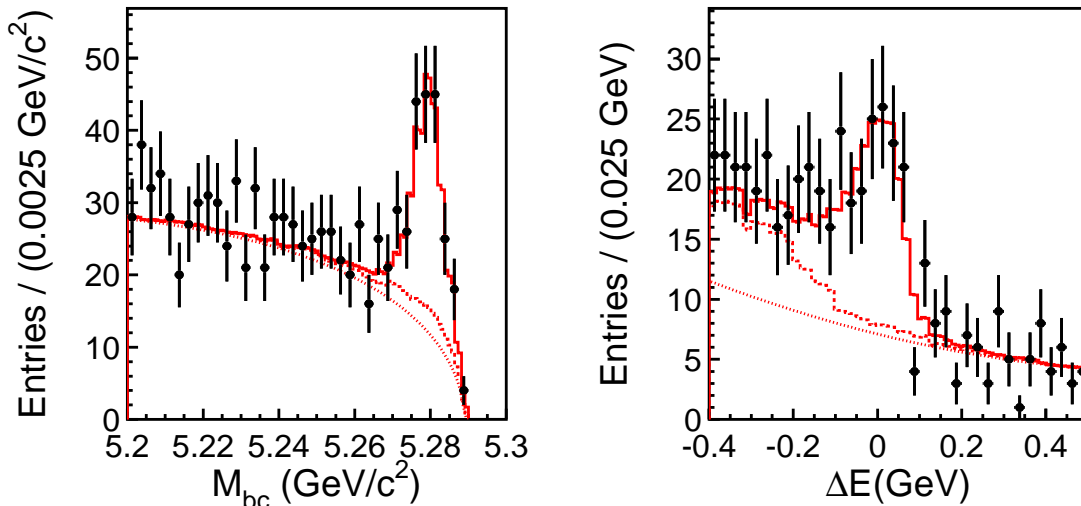


FIG. 1: (a)  $M_{bc}$  distributions within the  $\Delta E$  signal region and (b)  $\Delta E$  distributions within the  $M_{bc}$  signal (MR1 and MR2 combined). Solid curves show the fit to signal plus background distributions. Lower dashed curves show the background contributions from  $q\bar{q}$ . Upper dashed histogram show the sum of background contributions from  $q\bar{q}$  and  $B$  decays.

is determined from an unbinned two-dimensional maximum-likelihood fit to the  $\Delta E$ - $M_{bc}$  distribution. The fit region is chosen as  $-0.4 \text{ GeV} < \Delta E < 0.5 \text{ GeV}$  and  $5.2 \text{ GeV}/c^2 < M_{bc}$  to avoid other  $B\bar{B}$  background events that populate the low- $\Delta E$  high- $M_{K_S^0\pi^0}$  region. The signal distribution is represented by a PDF obtained from an MC simulation of  $B^0 \rightarrow K^{*0}\gamma$  and  $B^0 \rightarrow K_2^{*0}\gamma$  that accounts for a small correlation between  $M_{bc}$  and  $\Delta E$ . The background from  $B$  decays are also modeled with an MC simulation. For the  $q\bar{q}$  background, we use the ARGUS parameterization [15] for  $M_{bc}$  and a second-order polynomial for  $\Delta E$ . The normalizations of the signal and background distributions and the  $q\bar{q}$  background shape are the five free parameters in the fit. We observe a total of 260 candidates in the signal box in MR1, which decreases to 116 after flavor tagging and  $B$  vertex reconstruction, and obtain  $70 \pm 11$  signal events from the fit; the average signal purity over the six  $r$  intervals is  $63 \pm 11\%$ . In MR2, corresponding numbers are 236, 120,  $45 \pm 11$ , and  $41 \pm 11\%$ .

## CP ASYMMETRY MEASUREMENTS

We determine  $\mathcal{S}$  and  $\mathcal{A}$  from an unbinned maximum-likelihood fit to the observed  $\Delta t$  distribution. The probability density function (PDF) expected for the signal distribution,  $\mathcal{P}_{\text{sig}}(\Delta t; \mathcal{S}, \mathcal{A}, q, w, \Delta w)$ , is given by the time dependent decay rate [Eq. (1)] modified to incorporate the effect of incorrect flavor assignment. The distribution is convolved with the proper-time interval resolution function  $R_{\text{sig}}$ , which takes into account the finite vertex resolution. The parametrization of  $R_{\text{sig}}$  is the same as that used for the  $B^0 \rightarrow K_S^0\pi^0$  decay [11].  $R_{\text{sig}}$  is first derived from flavor-specific  $B$  decays [16] and modified by additional parameters that rescale vertex errors to account for the fact that there is no track directly originating from the  $B$  meson decay point.

For each event, the following likelihood function is evaluated:

$$\begin{aligned}
P_i = & (1 - f_{\text{ol}}) \int_{-\infty}^{+\infty} \left[ f_{\text{sig}} \mathcal{P}_{\text{sig}}(\Delta t') R_{\text{sig}}(\Delta t_i - \Delta t') \right. \\
& + (1 - f_{\text{sig}}) \mathcal{P}_{\text{bkg}}(\Delta t') R_{\text{bkg}}(\Delta t_i - \Delta t') \left. \right] d(\Delta t') \\
& + f_{\text{ol}} P_{\text{ol}}(\Delta t_i),
\end{aligned} \tag{2}$$

where  $P_{\text{ol}}$  is a Gaussian function that represents a small outlier component with fraction  $f_{\text{ol}}$  [17]. The signal probability  $f_{\text{sig}}$  is calculated on an event-by-event basis from the function which we obtained as the result of the two-dimensional  $\Delta E$ - $M_{\text{bc}}$  fit for the signal yield extraction. A PDF for background events,  $\mathcal{P}_{\text{bkg}}$ , is modeled as a sum of exponential and prompt components, and is convolved with a Gaussian which represents the resolution function  $R_{\text{bkg}}$  for the background. All parameters in  $\mathcal{P}_{\text{bkg}}$  and  $R_{\text{bkg}}$  are determined by a fit to the  $\Delta t$  distribution of a background-enhanced control sample, i.e. events outside of the  $\Delta E$ - $M_{\text{bc}}$  signal region. We fix  $\tau_{B^0}$  and  $\Delta m_d$  at their world-average values [18].

The only free parameters in the final fit are  $\mathcal{S}_{K_S^0 \pi^0 \gamma}$  and  $\mathcal{A}_{K_S^0 \pi^0 \gamma}$ , which are determined by maximizing the likelihood function  $L = \prod_i P_i(\Delta t_i; \mathcal{S}, \mathcal{A})$  where the product is over all events. We obtain

$$\begin{aligned}
\mathcal{S}_{K_S^0 \pi^0 \gamma} &= +0.08 \pm 0.41(\text{stat}) \pm 0.10(\text{syst}), \\
\mathcal{A}_{K_S^0 \pi^0 \gamma} &= +0.12 \pm 0.27(\text{stat}) \pm 0.10(\text{syst}).
\end{aligned}$$

We define the raw asymmetry in each  $\Delta t$  bin by  $(N_{q=+1} - N_{q=-1}) / (N_{q=+1} + N_{q=-1})$ , where  $N_{q=+1(-1)}$  is the number of observed candidates with  $q = +1(-1)$ . Figure 2 shows the raw asymmetries for the  $K_S^0 \pi^0 \gamma$  events. Note that these are simple projections onto the  $\Delta t$  axis, and do not reflect other event-by-event information (such as the signal fraction, the wrong tag fraction and the vertex resolution), which is in fact used in the unbinned maximum-likelihood fit for  $\mathcal{S}$  and  $\mathcal{A}$ .

## Systematic Error

Primary sources of the systematic error are (1) uncertainties in the resolution function ( $\pm 0.06$  for  $\mathcal{S}_{K_S^0 \pi^0 \gamma}$  and  $\pm 0.03$  for  $\mathcal{A}_{K_S^0 \pi^0 \gamma}$ ), (2) uncertainties in the vertex reconstruction ( $\pm 0.03$  for  $\mathcal{S}_{K_S^0 \pi^0 \gamma}$  and  $\pm 0.04$  for  $\mathcal{A}_{K_S^0 \pi^0 \gamma}$ ) and (3) uncertainties in the background fraction ( $\pm 0.07$  for  $\mathcal{S}_{K_S^0 \pi^0 \gamma}$  and  $\pm 0.03$  for  $\mathcal{A}_{K_S^0 \pi^0 \gamma}$ ). Effects of tag-side interference [20] contribute  $\pm 0.07$  for  $\mathcal{A}_{K_S^0 \pi^0 \gamma}$ . Also included are effects from uncertainties in the wrong tag fraction and physics parameters ( $\Delta m_d$ ,  $\tau_{B^0}$  and  $\mathcal{A}_{K^{*0} \gamma}$ ). Fitting a large sample of MC events revealed no bias in the fit procedure. The statistical errors from the MC fit are assigned as systematic errors. The total systematic error is obtained by adding these contributions in quadrature.

## Crosschecks

Various crosschecks of the measurement are performed. We apply the same fit procedure to the  $B^0 \rightarrow J/\psi K_S^0$  sample without using  $J/\psi$  daughter tracks for the vertex reconstruction [21]. We obtain  $\mathcal{S}_{J/\psi K_S^0} = +0.73 \pm 0.08(\text{stat})$  and  $\mathcal{A}_{J/\psi K_S^0} = +0.01 \pm 0.04(\text{stat})$ ,



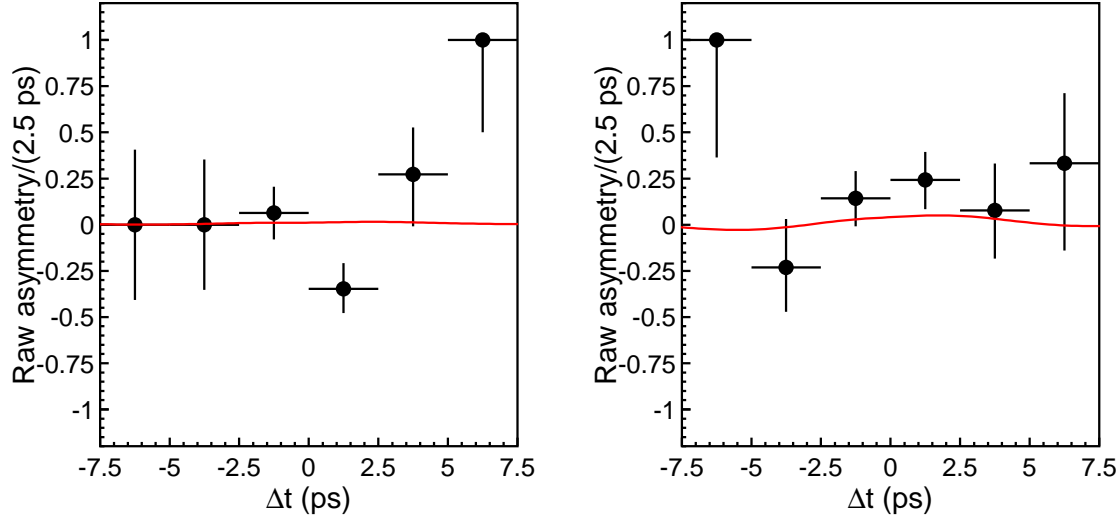


FIG. 2: Asymmetry in each  $\Delta t$  bin for  $B^0 \rightarrow K_S^0 \pi^0 \gamma$  with  $0 < r \leq 0.5$  (left) and  $0.5 < r \leq 1.0$  (right). Solid curves show the results of the unbinned maximum-likelihood fits.

which are in good agreement with the world-average values [19]. We perform a fit to  $B^+ \rightarrow K_S^0 \pi^+ \gamma$ , which is a good control sample of the  $B^0 \rightarrow K_S^0 \pi^0 \gamma$  decay, without using the primary  $\pi^+$  for the vertex reconstruction. The result is consistent with no  $CP$  asymmetry, as expected. Lifetime measurements are also performed for these modes, and values consistent with the world-average values are obtained. Ensemble tests are carried out with MC pseudo-experiments using  $\mathcal{S}$  and  $\mathcal{A}$  obtained by the fit as the input parameters. We find that the statistical errors obtained in our measurements are all within the expectations from the ensemble tests. Fits to the two  $M_{K_S^0 \pi^0}$  regions yield  $\mathcal{S} = +0.01 \pm 0.52(\text{stat}) \pm 0.11(\text{syst})$  and  $\mathcal{A} = +0.11 \pm 0.33(\text{stat}) \pm 0.09(\text{syst})$  for MR1, and  $\mathcal{S} = +0.20 \pm 0.66(\text{stat})$  and  $\mathcal{A} = +0.14 \pm 0.46(\text{stat})$  for MR2. The results are consistent with those from the full  $M_{K_S^0 \pi^0}$  sample.

## SUMMARY

We have performed a measurement of the time-dependent  $CP$  asymmetry in the decay  $B^0 \rightarrow K_S^0 \pi^0 \gamma$  with  $K_S^0 \pi^0$  invariant mass up to  $1.8 \text{ GeV}/c^2$ , based on a sample of  $386 \times 10^6 \ B\bar{B}$  pairs. We obtain  $CP$ -violation parameters  $\mathcal{S}_{K_S^0 \pi^0 \gamma} = +0.08 \pm 0.41(\text{stat}) \pm 0.10(\text{syst})$  and  $\mathcal{A}_{K_S^0 \pi^0 \gamma} = +0.12 \pm 0.27(\text{stat}) \pm 0.10(\text{syst})$ . We do not find any significant  $CP$  asymmetry, and therefore no indication of new physics from right handed currents, with the present statistics.

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- [1] M. Kobayashi and T. Maskawa, Prog. Theor. Phys. **49**, 652 (1973).
  - [2] D. Atwood, M. Gronau and A. Soni, Phys. Rev. Lett. **79**, 185 (1997).
  - [3] B. Grinstein, Y. Grossman, Z. Ligeti and D. Pirjol, Phys. Rev. D **71**, 011504 (2005).
  - [4] D. Atwood, T. Gershon, M. Hazumi and A. Soni, Phys. Rev. D **71**, 076003 (2005).
  - [5] S. Kurokawa and E. Kikutani, Nucl. Instr. and Meth. A **499**, 1 (2003).
  - [6] BABAR Collaboration, B. Aubert *et al.*, Phys. Rev. Lett. **93**, 201801 (2004).
  - [7] Belle Collaboration, Y. Ushiroda *et al.*, Phys. Rev. Lett. **94**, 231601 (2005).
  - [8] Belle Collaboration, A. Abashian *et al.*, Nucl. Instr. and Meth. A **479**, 117 (2002).
  - [9] Y. Ushiroda (Belle SVD2 Group), Nucl. Instr. and Meth. A **511**, 6 (2003).
  - [10] Belle Collaboration, P. Koppenburg *et al.*, Phys. Rev. Lett. **93**, 061803 (2004).
  - [11] Belle Collaboration, K. F. Chen *et al.*, Phys. Rev. D **72**, 12004 (2005)
  - [12] R. A. Fisher, Annals Eugen. **7**, 179 (1936).
  - [13] Belle Collaboration, K. Abe *et al.*, Phys. Rev. Lett. **91**, 261801 (2003).
  - [14] H. Kakuno, K. Hara *et al.*, Nucl. Instr. and Meth. A **533**, 516 (2004).
  - [15] ARGUS Collaboration, H. Albrecht *et al.*, Phys. Lett. B **241**, 278 (1990).
  - [16] Belle Collaboration, K. Abe *et al.*, hep-ex/0408111.
  - [17] Belle Collaboration, K. Abe *et al.*, Phys. Rev. D **71**, 072003 (2005) ; H. Tajima *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **533**, 370 (2004).
  - [18] Heavy Flavor Averaging Group, <http://www.slac.stanford.edu/xorg/hfag/>.
  - [19] S. Eidelman *et al.*, Phys. Lett. B **592**, 1 (2004).
  - [20] O. Long, M. Baak, R. N. Cahn and D. Kirkby, Phys. Rev. D **68**, 034010 (2003).
  - [21] Belle Collaboration, K. Abe *et al.*, hep-ex/0507037